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TEMPORARY AUDITORY-THRESHOLD SHIFTS INDUCED BY REPEATED TEN-MINUTE EXPOSURES TO CONTINUOUS TONES IN WATER

by

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Naval Medical Research and Development Command
Research Work Unit M0096.002-1047

Released by:

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SUMMARY PAGE

THE PROBLEM

To develop a data base upon which to establish hearing-conservation standards for Navy divers exposed to noise emanating from hand-held tools.

THE FINDINGS

Bare-headed divers exposed to continuous tones for ten minutes in water at sound pressure levels between 125 and 150 decibels above 20 micropascal incurred moderate temporary auditory-threshold shifts. For the octave band centered at 700 Hz, noise intensity levels must not exceed permitted levels for exposure to that octave band in air. For the 1400 Hz octave band, permissible exposure intensity levels are 5 to 15 dB greater for in-water exposures than for in-air exposures. For an octave band of noise centered at 5600 Hz, exposure intensity levels in water must be at least 5 dB lower than exposure levels permitted in air.

APPLICATION

These findings contribute to the establishment of a hearing-conservation standard for Navy divers exposed to intense noise in water.

ADMINISTRATIVE INFORMATION

This research was carried out under Naval Medical Research and Development Command Work Unit M0096.002-1047 "Development of an interim hearing conservation standard for hand-held underwater tools." It was submitted for review on 27 December 1985, approved for publication on 19 September 1988, and designated as NSMRL Report No. 1122.

ABSTRACT

Four divers were exposed successively for ten minute periods to pure tones of 5600, 1400, and 700 hertz (Hz) (in that order) in air at 100 decibels above 20 micropascal and in water at various sound pressure levels between 125 and 150 decibels above 20 micropascal. Divers incurred moderate temporary auditory-threshold shifts (TTS) from all exposures. Equivalent amounts of TTS are produced in water as in air by the same sound intensity levels (SIL) at 700 Hz, by 5 to 15 dB greater SIL in water at 1400 Hz, and by smaller SILs in water at 5600 Hz.

INTRODUCTION

As powered underwater hand-held tools became available, the Navy had a pressing need to establish guidelines for assessing the effects of noise produced by those tools on divers' hearing. Smith (1983) proposed an interim procedure that was based upon the concept that noises of equal sensory magnitude are comparably hazardous. Under the proposed procedure water-borne tool noise is measured in octave bands. From each octave band level the normative underwater hearing threshold level would be subtracted yielding an estimate of the sensation level (sensory magnitude) for that band. Then, that sensory magnitude would be added to normative threshold data for hearing in air to arrive at an estimate of the band level in air that would be of comparable sensory magnitude to the band in water. The data proposed to be used as "normative" for underwater hearing threshold levels were those of Brandt and Hollien (1967). The interim procedure was accepted by the Medical Department and is now in use in the Acceptance for Navy Use (ANU) program. This experiment and that of Smith and Wojtowicz (1985) were undertaken to test the validity of the equal sensory magnitudes hypothesis.

Smith and Wojtowicz (1985) planned to compare magnitudes of temporary auditory-threshold shift (TTS) produced in water with TTS produced by exposures in air. The differences between stimulus intensities in the two media which produced comparable magnitudes of TTS at selected frequencies would provide a basis for generating permissible exposure levels for exposure to noise in water. Their report documented the effects of exposure for twenty-five minutes to intense continuous tones in water at sound pressure levels (SPLs) comparable to those produced by some hand-held underwater tools (Smith and Wojtowicz, 1985). However, the magnitudes of TTS obtained from the in-water exposures were very much larger than anticipated and, in five of the eight ears exposed, required more than twenty-four hours for recovery. Quite apart from an ethical proscription against inflicting larger than necessary TTS on subjects, the magnitudes of TTS obtained (up to 55 dB) made it virtually impossible to create comparable magnitudes of TTS from noise exposure in air without greatly exceeding existing hearing-conservation regulations (Chief of Naval Operations, 1983). Accordingly, the measurements reported herein were undertaken in order to determine the minimum noise exposure conditions in water that would reliably produce moderate amounts of TTS.

II. METHOD

Subjects. The subjects were four Navy divers who had normal hearing levels at the frequencies of interest. Two had moderate high frequency hearing impairments and were not exposed to the highest frequency employed in this experiment. None had hearing threshold levels (HTLs) in excess of 20 dB at the frequencies to which they were exposed or at which TTS was measured. None had any prior experience as subjects in psychoacoustic experiments.

Apparatus and exposure environments. The apparatus and exposure environments used were essentially the same as those previously reported (Smith and Wojtowicz, 1985). In-water exposures were done at a depth of 20' with the divers using open-circuit self-contained underwater breathing apparatus (SCUBA) in a 35' deep indoor pool at the Newport Laboratory of the Naval Underwater Systems Center. Intense tones in water were projected by one of two sources; a Honeywell HX-188 or an Underwater Sound Reference Detachment (NRL-USRD) type F56 transducer. An NRL-USRD F50 hydrophone was used to measure underwater sound levels. Fatiguing tones were delivered monaurally in air through a TDH 39 earphone. Temporary auditory-threshold shifts were determined using a single-frequency threshold test administered with the use of a Grason-Stadler model E3262A recording attenuator. At pool-side, an Eckel Industries Eckoustic booth was used for hearing-threshold measurements.

Hearing tests. Conventional audiometry using a Tracoustics Program III clinical audiometer was performed each day at NSMRL on all divers prior to departure for the test site. Also, at the test site, thresholds were measured with a recording attenuator at a single test frequency which was one-half octave above the frequency to which the subject was about to be exposed. This test was repeated immediately following each noise exposure. TTS was computed as the difference between the pre-exposure and post-exposure single-frequency tests. The amount of TTS existing two minutes following the exposure (TTS_2) was used to compare results across conditions.

Procedure. On the first day of the experiment all divers were administered audiograms and given training on procedures used to measure TTS. On the basis of the audiograms, each diver's more sensitive ear was designated as his "test ear".

Following establishment of a baseline on the test ear, ten-minute noise exposures were administered by earphone at 100 dB SPL. Permissible exposure time to a sound level of 100 dB is thirty minutes per day (constituting a Navy-defined daily noise dose of 1.0 (Chief of Naval Operations, 1983). Thus, the each individual exposure to 100 dB for ten minutes comprised a noise dose of 0.33. Exposures (separated by at least 45 minutes) were administered at 5600, 1400, and 700 Hz (in that order) with fixed-frequency test frequencies being 8000, 2000, and 1000 Hz respectively. The order of exposure administration capitalizes on the fact that little TTS is produced at frequencies below the exposure frequency.

On each of the three following days each diver made three twelve-minute dives using open-circuit self-contained underwater breathing apparatus. The divers wore wet or dry suits but no hoods. On the first dive-day, prior to the first dive, baseline thresholds were measured at 8000 Hz for both ears. The surface-tended diver then dove at a rate not in excess of 1/2 foot per second to 20' and positioned himself on a sling facing the sound source. The diver was then exposed to a tone at 70 dB above 20 micropascal[1] at 5600 Hz and asked by pre-arranged line signal if that signal level was tolerable. If it was, the sound level was increased by ten dB. That procedure was repeated until the maximum tolerable level not greater than 130 dB was reached. The subject was then exposed at that level for ten minutes. Upon completion of the exposure, the diver surfaced slowly (1/2 foot per second), left the water, dried his head, entered the audiometric booth, and began tracing his threshold on the fixed-frequency test, test ear first.

After all divers had been exposed to the first 5600 Hz fatiguing tone, the median TTS_2 was computed for the test ear. The level for the next exposure of the day was determined in consultation with the divers and on the basis of the median results from the prior exposure according to the following rules:

1. If the median TTS_2 was zero, the next exposure level would be 10 dB higher than the previous exposure level.

2. If median TTS_2 did not exceed 10 dB, the next exposure level would be 5 dB higher than the previous exposure.

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1 The reference sound pressure used throughout this report is 20 micropascal. Reference sound intensity is 10^{-12} watts per square meter.

3. If the median TTS_2 was higher than 10 dB but not greater than 20 dB, the next exposure level would be 5 dB lower than the previous level.

4. If the median TTS_2 was in excess of 20 dB, the next exposure level would be at least 10 dB lower than the previous exposure level.

5. Residual TTS from any prior exposure could be not more than 10 dB before a diver would be exposed again.

As experience accumulated and circumstances leading to specific results were evaluated, these rules were modified. In no case, however, was a subsequent exposure level set more than ten dB higher than the immediately preceding level. It was frequently impossible to take measurements of TTS sooner than three minutes after the exposure terminated because of delays in getting the diver from the diving stage to the audiometric booth. In those cases TTS_2 was estimated from recovery trends over the three-minute post-exposure tests.

Procedures for the second and third days were the same as described above except for the frequencies used. On the first diving day the exposure frequency was 5600 Hz and only two divers were used. On the second and third days, the exposure frequencies were 1400 Hz and 700 Hz respectively and all four divers were run.

III. RESULTS

Table I shows the results for the exposures in air. They will be discussed below.

Table I

Median temporary auditory-threshold shifts existing two minutes after ten-minute exposures to pure tones at 100 dB SPL in air.

	Exposure Frequency, hertz		
	700	1400	5600
Median TTS_2	6.2	9.8	5.0
Range	5.5	8.5	6.0
Number of divers	4	4	2

The results for the exposures in water are summarized in Table II. The order in which those results were generated is as follows:

<u>Dive day #1, 5600 Hz</u>: TTS measured four minutes after the 130 dB exposure was 0 dB for diver A and 20 dB for diver B. The estimated TTS_2 for diver B was 24 db (yielding the tabled median of 12 dB. His contralateral (non-test) ear, which was farther from the source, incurred a TTS measured eight minutes after the exposure of 5 dB. The large TTS observed in Diver B's test ear was very likely spurious because he recovered rapidly with TTS being 0 dB at 31 min after the exposure. Hence, the median TTS_2 of 12.0 dB shown in Table 1 for exposure to 5600 Hz at 130 db is also spuriously large. Nevertheless, according to the rules of procedure, the next exposure level was set at 125 dB and median TTS_2 was 8.5 dB (8 and 9 dB). The final exposure level was 135 dB which produced a median TTS_2 of 9.5 dB (3 and 16 dB).

<u>Dive day #2, 1400 Hz</u>: All four divers were run. Median TTS_2 from the 130 dB exposure was 3 dB with a range of 0 to 6 dB. The next exposure level was set at 140 dB and median TTS_2 was 5 dB (range 2 to 10 dB). The final exposure level was 150 dB which produced a median TTS_2 of 16.5 dB (13 to 21 dB).

<u>Dive day #3, 700 Hz</u>: Median TTS_2 for the four divers from the 130 dB exposure was 5 dB with a range of 0 to 10 dB. The next exposure level was set at 135 dB and median TTS_2 was 6.5 dB (range 5 to 13 dB). The final exposure level was 140 dB which produced a median TTS_2 of 8 dB (1 to 12 dB).

Table II

Median temporary auditory-threshold shifts existing two minutes after ten-minute exposures to intense pure tones in water.

Dive day	3	2	1
Exposure level	Exposure Frequency, hertz		
(dB)	700	1400	5600
125			8.5
130	5.0	3.0	12.0
135	6.5		9.5
140	8.0	5.0	
150		16.5	
Number of divers	4	4	2

The results in Table II may be compared with those in Table I in order to estimate what exposure levels would produce comparable amounts of TTS in water and in air. The results of that comparison are shown in Table III.

Table III

Exposure sound pressure levels in water producing comparable amounts of temporary auditory-threshold shifts to those induced by ten minute exposures at 100 dB in air and the corresponding differences in intensity level.

Frequency (hertz)	Sound Pressure Level (dB)	Sound Intensity Level Difference in-water vs in-air (dB)
700	135	0
1400	140-150	5-15
5600	< 125	<-5

The second column in Table III gives the SPL (or the range of SPL) in water that produced approximately the same TTS in water as was produced by the 100 dB fatiguer in air. The third column in Table III shows the difference in intensity levels between the exposures administered in air at 100 dB and exposures in water given in column 2. (For equal sound pressures, a tone in water is approximately 35 dB less intense than a tone in air. Thus, reasonable estimates of comparable sound intensity levels (SILs) in the two media may be obtained simply by subtracting 35 dB from SPLs measured in water.) The same SIL in water and in air at 700 Hz produced comparable amounts of TTS. At 1400 Hz, noise intensities of from 5 to 15 dB higher in water than in air were required to produce about the same TTS. At 5600 Hz, the water-immersed ear incurred more TTS than was induced by a 5 dB higher SIL in air.

IV. DISCUSSION

Apart from the small number of subjects used, two important potential sources of contamination must be kept in mind in evaluating the results. First, hearing thresholds of divers who have just exited the water often appear elevated either because some water may remain in the ear canal, or equalization of trans-tympanic-membrane pressures may be incomplete due to slight congestion. For example, Diver B, discussed above, apparently incurred a threshold shift that was not due to noise exposure. Second, although sufficient time (45 to 60 minutes) should have elapsed between successive exposures on a given day to allow recovery from any TTS previously induced, the potential for "latent TTS" to accumulate is not negligible (Harris, 1955).

The growth of TTS with exposure intensity is curvilinear being a slowly increasing function of exposure level for low intensities and greatly accelerating beyond some critical level (Hirsh and Bilger, 1955; Ward, 1963). The low rate of growth of TTS as a function of intensity for the 700 Hz fatiguer suggests that exposure levels at that frequency were quite moderate (Ward, et al., 1958, 1959). The 1400 Hz fatiguer produced similar low growth between 130 and 140 dB with an acceleration evident between the 140 and 150 dB exposure levels roughly equivalent to what one might see in air for a ten dB increase in exposure level in the 90 to 110 dB SPL range (Ward, 1963). For the 5600 Hz fatiguer, the growth rate is also quite low again suggesting moderate exposure levels.

Montague and Strickland (1961) found that at 1500 Hz, divers would not tolerate exposure to SPLs in excess of 165 to 175 dB or about 40 to 50 dB (5 to 15 dB IL) higher than tolerance levels in air. The present results at 1400 Hz are in good agreement with their finding.

In an earlier experiment, Smith et al. (1970) found that 3500 Hz tones in water had to be approximately 33 dB more intense than tones of that frequency in air in order to produce equivalent magnitudes of TTS. Those data were obtained from swimmers near the surface breathing by snorkel. Still earlier, Smith (1969) had found that underwater hearing thresholds of breath-holding (not snorkeling) subjects were about five dB higher at 3000 to 4000 Hz than for divers on SCUBA. It is doubtful that the differences between the Smith, et al. (1970) results at 3500 Hz and the results here for the 1400 Hz fatiguer can be attributed entirely to differences in the breathing apparatus used. Commenting upon the lower intensity correspondence at 1900 Hz (air vs water) found by Montague and Strickland (1961), Smith et al. (1970) suggested that the ear's susceptibility to noise in water may be frequency dependent. The present results tend to support and extend that view.

In a more recent theoretical paper, Smith (1985) suggested that the water-immersed ear may be more sensitive to noise at high frequencies (above about 8000 Hz) than it is in air. The present results indicate that increased susceptibility to noise-induced hearing damage in water may occur at frequencies as low as 5600 Hz.

These results and those of Smith and Wojtowicz (1985) have implications for the validity of the equal sensory magnitude procedure (Smith, 1983). Smith and Wojtowicz (1985) found the proposed procedure not to be valid for sensory magnitudes in excess of 85 dB. Using the methods of the equal sensory magnitude procedure to evaluate the stimuli used in the present experiment, the exposures in water at 130 dB would correspond to exposure levels in air of approximately 76 dB at 700 Hz, 70 dB at 1400 Hz, and 63 dB at 5600 Hz. Clearly, exposures at those levels for ten minutes would not produce any measurable TTS in typical subjects. Also, the 150 dB exposure in water at 1400 Hz produced a median TTS_2 of 16.5 dB. The sensory magnitude procedure would estimate that the corresponding exposure level in air would be 90 dB. However, these subjects yielded a median TTS_2 of 9.8 dB for a 100 dB exposure in air. Except for the 3000 to 4000 Hz frequency region (Smith et al., 1970) there appears to be little or no correlation between the effects predicted by the sensory magnitude procedure and data now available.

Since two experiments found problems with the equal sensory magnitudes method of assessing underwater noise hazards, that procedure ought to be considered invalid. In attempting to understand why this is so several possibilities must be considered. First, small numbers of divers were used in both experiments and both experiments are fraught with other procedural problems as well. Nevertheless, both sets of data indicate that the effects of underwater noise exposure on hearing are not well predicted, indeed, may be severely underestimated, by Smith's (1983) proposal. Second, the Brandt and Hollien (1967) data, used as "normative" for underwater hearing threshold levels, may be invalid. A possibility exists that all reported underwater hearing thresholds have been masked thresholds. When the ears are occluded by any means body sounds not normally heard are audible to subjects. Thus, when diving even in very quiet water, the ears are occluded by the water and circulatory noises (always present at the tympanic membrane) are audible to divers. Sivian (1947) had estimated that, at 1000 Hz and 3000 Hz, hearing in water may be only about 5 to 10 dB less sensitive (on an intensity basis) than in air. He did allow that other factors might operate to elevate the underwater threshold by about another 10 dB. No one (including Sivian) has ever measured hearing thresholds in water that were quite so low (Smith, 1969, 1985). A third possibility that might explain the failure of the equal sensory magnitudes procedure is that the dynamic range of the water-immersed ear is not as large as that of the ear in air. Montague and Strickland (1961) suggest that that might be the case at least at 1500 Hz.

CONCLUSIONS

Considering the scant data obtained in this and previous experiments one must conclude that insufficient data are on hand to recommend damage risk criteria for exposure to noise in water. Clearly, additional data, taken on larger numbers of subjects, are required for that purpose. A further caution must be stated: all four experiments that have been done to date have used pure tones as fatiguing stimuli. While generalizations from pure-tone exposures to broad band exposures are possible, they must be made carefully. With those points as a caveat, it may be tentatively concluded that:

For the octave band centered at 700 Hz, noise intensity levels in water should not exceed those for exposure to that octave band in air.

For an octave band of noise centered at 1400 Hz, exposure intensity levels may be 5 to 15 dB greater for in-water exposures than for in-air exposures.

From Smith et al. (1970), for an octave band of noise centered at 3500 Hz, noise intensity levels may be as much as 33 dB higher in water than in air.

For an octave band of noise centered at 5600 Hz, exposure intensity levels in water must be at least 5 dB lower than exposure levels permitted in air.

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Four divers were exposed successively for ten minute periods to pure tones of 5600, 1400, and 700 hertz (Hz) (in that order) in air at 100 decibels above 20 micropascal and in water at various sound pressure levels between 125 and 150 decibels above 20 micropascal. Divers incurred moderate temporatory auditory-threshold shifts (TTS) from all exposures. Equivalent amounts of TTS are produced in water as in air by the same sound intensity levels (SIL) at 700 Hz, by 5 to 15 dB greater SIL in water at 1400 Hz, and by smaller SILs in water at 5600 Hz.

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